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Stephen J. Licata and Frank W. Burcham, Jr.
NASA Ames Research Center, Dryden Flight Research Facility, Edwards, California 93523

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Edwards, California 93523

INTRODUCTION

The ability to achieve rapid and reliable airstarts is crucial to the safe operation of modern jet aircraft. The NASA Dryden Flight Research Facility is currently testing an engine equipped with a prototype digital electronic engine control (DEEC) in an F-15 airplane. Advantages of the digital control over engine control systems now in use are: more inputs and outputs of engine parameters into the control system, computing capability that is both faster and more accurate than possible at present, and extensive self-test features and fault accommodation (refs. 1 and 2). One of the significant features of the DEEC is an improved airstart capability. The DEEC incorporates closed-loop airstart logic. The airstart logic has been tested in an altitude facility at the Arnold Engineering and Development Center (ref. 3). This report presents the flight evaluation of the DEEC airstart capability and a comparison to the results of altitude facility tests.

SYMBOLS AND ABBREVIATIONS

SEC	secondary engine control
CIVV	compressor inlet variable vanes
DEEC	digital electronic engine control
FTIT	fan turbine inlet temperature, °C
HP	pressure altitude, m
JFS	jet fuel starter
M	Mach number
N1	engine fan speed
N2	engine core speed, percent (100 percent is 14,000 rpm)
PB	main burner pressure
PLA	power lever angle, deg
PS2	engine inlet static pressure
PT6M	mixed turbine discharge pressure
RCVV	rear compressor variable vanes
TT2	engine inlet temperature
WF	engine fuel flow, kg/hr

DESCRIPTION OF APPARATUS

The F-15 aircraft (fig. 1) is a single seat, high performance, all-weather air superiority fighter capable of Mach 2.5. It is a twin-engine airplane with a high-mounted sweptback wing, twin vertical stabilizers, and large horizontal stabilizers. The F-15 has been modified to be a general test bed. The specific modification for the DEEC flight test program was the replacement of the left engine with a special F100 engine equipped with a DEEC system.

The F100 engine (figs. 2 and 3) is a twin spool, low bypass ratio augmented turbofan. It has a three-stage fan driven by a two-stage low pressure turbine. The 10-stage high-pressure compressor is driven by a 2-stage high-pressure turbine. A compressor bleed is used only during starting. The variable camber inlet guide vanes and rear compressor vanes allow for higher performance over the operating flight envelope. Variable augmented thrust is provided by a mixed flow, five-segment afterburner. The mixed flow is exhausted through a variable area convergent-divergent nozzle. For these tests, engine serial number P680063 was used. It had been updated to an F100(3) production engine configuration prior to the DEEC installation.

The DEEC is a full-authority digital electronic control system with a simple integral hydromechanical secondary engine control. DEEC replaces the functions of the supervisory electronic engine control and hydromechanical unified fuel control on the standard F100 engine. The DEEC system, shown in figure 4, receives inputs from (a) the airframe through throttle position (PLA) and Mach number (M); (b) the engine through pressure sensors PB, P6TM, and PS2, temperature sensors TT2 and FTIT, rotor speed sensors N1 and N2; and (c) the control system through feedback resolvers that indicate variable vane (RCVV, CIVV) positions, metering valve positions (fuel flow for primary and augmented thrust modes), and exhaust nozzle positions. This information is used by the DEEC controller to (a) schedule the compressor bleeds and position the variable vanes through actuators in an open-loop system; (b) control primary and augmented fuel flow in a closed-loop system; and (c) control nozzle in a closed-loop system.

The DEEC computer is a 16-bit, 1.2-μsec cycle time microcomputer with 10.5K of available memory. The entire electronic unit is fuel cooled.

The DEEC secondary engine control (SEC) is a purely hydromechanical engine fuel control. It is integrated within the gas generator fuel metering hardware of the DEEC. In the event of a critical DEEC failure, or at the pilot's option, the SEC system can be engaged. The SEC inputs are PLA, TT2, PS2, and RCVV position. Based on these parameters, the SEC system controls the engine fuel flow, the RCVV position, and the compressor start bleed.

The jet fuel starter (JFS) is a small auxiliary gas turbine power unit which can be coupled to the F100 engine. The JFS is used to accelerate the high compressor for engine starting on the ground or in flight.

Pressures, temperatures, rotor speeds, fuel flow, and positions of variable geometry are measured at various stations in the F100 engine. Engine parameters important to this report are PLA, N2, FTIT, and WF. All parameters are input into a pulse code modulation (PCM) system during the test flights. The digital PCM data are recorded on an onboard tape recorder and also telemetered to the ground for real-time display in the control room.

DEEC AIRSTART LOGIC

In the event of an engine shutdown or flameout, the DEEC monitors several parameters to insure a successful airstart. A simplified block diagram of DEEC airstart logic is given in figure 5. An open-loop fuel scheduling routine is used until the burner "light" (fuel mixture ignition) is indicated by a rise in the FTIT signal. Once the burner light has been detected by the DEEC, fuel flow and compressor bleed control switches to the closed-loop logic shown in the figure. This logic attempts to maintain a desired N2 rate by varying fuel flow. The desired N2 rate is a function of PT2, TT2, and M. If the fuel flow is too high the compressor will stall, resulting in a "hot start." If the fuel flow is too low, the energy available will not be sufficient to overcome the losses in the engine and the accessory power drain, resulting in a "hung start." The DEEC airstart logic maintains the optimal N2 rate subject to a bias if FTIT exceeds a limit of approximately 760° C. The minimum fuel flow set by a stop in the fuel metering valve is approximately 115 kg/hr. The compressor bleeds are held open until 56 percent N2 is attained. At airspeeds below approximately 200 knots, the DEEC airstart logic is designed to light the burner and maintain N2, but not to accelerate the engine to idle.

The jet fuel starter may also be used to assist in airstarts. For JFS-assisted airstarts, the DEEC uses a higher scheduled N2 rate and a lower FTIT limit. Compressor bleeds are held open until 56 percent N2 is achieved.

TEST PROCEDURE

This report is concerned with the ability of the DEEC-equipped F100 engine to perform airstarts with and without a JFS assist. The three types of airstarts examined are 40-percent spooldown, 25-percent spooldown, and JFS assist.

The spooldown airstart is achieved in a four-step procedure: engine shutdown, pressurization, light, and acceleration of the engine to idle speed. The engine shutdowns were mostly performed from the intermediate power setting. The engine spool (compressor rotor) is then allowed to wind down (spooldown) to a predetermined percentage of maximum core speed. For the evaluation of DEEC airstart capability, values of 40-percent N2 and 25-percent N2 were used. The pressurization step is accomplished when the pilot returns the throttle to the idle power setting to begin the start cycle. This pressurizes the fuel system, and fuel begins to flow to the combustor. Approximately 10 sec later, the fuel reaches the combustor nozzles and is ignited (light). The fuel flow is modulated by the DEEC to maintain the scheduled N2 rate until the scheduled idle speed is reached and the airstart sequence is completed.

The JFS-assisted airstart is accomplished by coupling the jet fuel starter to the high compressor rotor through a gearbox. The JFS may be engaged at any N2 speed from 0 to 30 percent. It accelerates the core rotor to approximately 30 percent. The pressurization step may be initiated at a core speed of 12 percent or greater. The JFS disengages at 50-percent N2.

Of the 53 primary DEEC airstarts attempted during the test flights, 21 were 40-percent spooldown, 24 were 25-percent spooldown, and 8 were JFS assisted. Airstart time is calculated from the pressurization step to idle in the above procedure. For all airstarts the normal F-15 power requirements for the engine and accessories were present.

During the airstart tests, the pilot used the right engine of the F-15 aircraft to maintain the desired airspeed and altitude. Airspeed was held within 4 knots and altitude within 30 m of the desired test conditions. Test day temperatures varied as much as ±10° C from standard day temperatures. More details of the test procedure can be found in reference 2.

RESULTS AND DISCUSSION

Spooldown Airstarts

Figure 6 is a time history of a DEEC airstart at an airspeed of 250 knots and an altitude of 9100 m, which also illustrates the use of closed-loop airstart logic. The engine was shut down at t = 10 sec. Immediately after shutdown there was a corresponding drop in core speed (N2), fan turbine inlet temperature (FTIT), and fuel flow to the engine (WF). The pilot initiated the ignition sequence by moving the throttle up over the idle detent to the idle power setting at t = 22 sec as the core rpm reached 40 percent. At this point the fuel flow began at the minimum value of 115 kg/hr. At t = 31 sec, the fuel mixture was ignited (light) as noted by the increase in FTIT. The DEEC closed-loop logic modulated the fuel flow to achieve the desired rate of acceleration of the engine core. N2 increased uniformly to t = 45 sec, sec, then increased more rapidly. Idle speed was reached at t = 77 sec. FTIT varied between 450 and 520° C during the airstart. The time required for the air start, defined as the difference between idle and pressurization times, was 55 sec.

Figure 7 shows another airstart at the same flight conditions of 250 knots, 9100 m, but for a 25-percent spooldown. Shutdown occurred at t = 7 sec. The engine spooled down to 25 percent at t = 39 sec, and the light occurred at t = 47 sec. The engine spooled up at a nearly constant rate, reaching idle at t = 111 sec. The FTIT stayed below 500° C during the airstart. The airstart time was 72 sec, as compared to 55 sec for the 40-percent spooldown airstart.

Airstarts at lower airspeeds took longer due to the reduced energy of the inlet flow, lower burner pressures, and lower stall margin. Figure 8 shows a 40-percent spooldown airstart at an airspeed of 200 knots and an altitude of 9250 m. Shutdown time was t = 12 sec, pressurization at t = 23 sec, light at 32 sec, and idle at t = 108 sec. Airstart time was 86 sec. The FTIT reached 600° C at t = 38 sec, with fuel flow on the minimum flow stop.

The 25-percent spooldown airstart at VC = 200 knots is shown in figure 9, at an altitude of 7600 m. Shutdown occurred at t = 3 sec, pressurization at t = 28 sec, light at t = 34 sec. The fuel flow was on the minimum stop from pressurization to t = 70 sec, and FTIT again reached 600° C. The airstart was completed at t = 139 sec for a time of 111 sec.

The effects of altitude were evaluated by performing airstarts at VC = 250 knots and 200 knots at several altitudes. Examples of spooldown airstarts at VC = 200 knots and an altitude of 4600 m are shown in figures 10 and 11. A 40-percent spooldown airstart is shown in figure 10. Shutdown occurred at t = 9 sec, pressurization at t = 15 sec, and light at t = 23 sec. Following the light, the N2 continued to decrease for 10 sec as fuel flow was increased. At t = 40 sec, a positive N2 rate was achieved and fuel flow was cut back as FTIT reached 600° C. In the time between t = 50 and 70 sec, oscillations in N2, FTIT, and WF occurred indicating that the gains in the closed-loop control logic were slightly too high. The airstart continued and idle was reached at t = 104 sec, for an airstart time T = 89 sec, slightly longer than the 86-sec time from figure 8 at the higher altitude but similar airspeed.

The 25-percent spooldown airstart at VC = 200 knots at an altitude of 4600 m is shown in figure 11. Shutdown occurred at t = 16 sec, pressurization at t = 33 sec, and the burner light occurred at t = 42 sec. The airstart proceeded normally, although some oscillations are noted between t = 70 and 90 sec. The frequency of these oscillations was similar to that seen in figure 10, but the amplitude was much smaller. The airstart was completed at t = 130 sec for an airstart time, T, of 97 sec, somewhat faster than the 111 sec of figure 9.

JFS-Assisted Airstarts

For more rapid airstarts at altitudes below 6100 m, the jet fuel starter was used for assisted airstarts. Figure 12 shows a time history of a JFS-assisted airstart at VC = 255 knots at an altitude of 6100 m. Shutdown occurred at t = 11 sec, and the JFS was engaged at t = 33 sec at an N2 of 25 percent. The N2 increased as a result of the JFS assist and stabilized at N2 = 32 percent. The pressurization was delayed for this test until stable JFS motoring speed was observed at t = 68 sec. After the light at t = 79 sec, N2 increased rapidly and idle was achieved at t = 106 sec for an airstart time of 38 sec.

A more typical JFS-assisted airstart in which the pressurization occurred immediately after JFS engagement is shown in figure 13 at VC = 345 knots at an altitude of 5200 m. Shutdown occurred at t = 13 sec. At this relatively high airspeed the N2 spooldown was slow, and N2 was decreasing slowly through 21 percent when the JFS was engaged at t = 59 sec, followed immediately by pressurization. Light occurred at 73 sec and idle was reached at t = 96 sec for an airstart time of 37 sec.

A JFS-assisted airstart at a lower speed of VC = 210 knots at an altitude of 6100 m is shown in figure 14. Shutdown occurred at t = 14 sec, JFS engage at t = 34 sec, pressurization at t = 36 sec, and light at t = 46 sec. The N2 rate was reduced to nearly zero at t = 65 sec prior to JFS disengage. Following the JFS disengage the N2 rate increased. The airstart was completed at t = 83 sec, for an airstart time of 47 sec.

All JFS-assisted airstarts attempted were successful from VC = 200 to 400 knots over a wide range of altitudes.

Summary of Airstart Times

Airstart times, T, for the DEEC airstarts are shown in figure 15 for the 40-percent spooldown airstarts, in figure 16 for the 25-percent spooldown airstarts, and in figure 17 for JFS-assisted airstarts. Airstart times for the 40-percent spooldown airstarts (figure 15) were approximately 50 sec at VC = 250 knots, 85 sec at VC = 200 knots, and up to 192 sec at VC = 175 knots. For the 25-percent spooldown airstarts, times were approximately 65 sec at VC = 250 knots, and from 97 to 135 sec at airspeeds of 205 to 210 knots. It is clear that 25-percent spooldown airstarts at VC = 200 knots are only marginally successful due to the long start times. Effects of altitude on airstart time are somewhat inconsistent, particularly at VC = 200 knots. For VC = 250 knots, the airstart times are plotted as a function of altitude in figure 18. No strong trends are evident, but there seems to be some trend toward slightly faster airstarts at intermediate altitudes of 6000 to 8000 m.

Unsuccessful Airstarts

At airspeeds below 200 knots, most of the spooldown airstarts were unsuccessful. This is not surprising since at these low airspeeds, the DEEC logic is only designed to light the burner and maintain rpm until the pilot can increase airspeed. The unsuccessful airstarts were mostly hung starts, in which the N2 either decreased or did not increase. A typical example of a hung start is shown in figure 19, a 25-percent spooldown airstart attempt at VC = 180 knots at an altitude of 7600 m. Following the light, N2 increased very slowly to 28 percent and then stabilized. The fuel flow remained on the minimum flow stop, and FTIT initially exceeded 600° C and then slowly decreased.

Only one hot start occurred in the airstart tests; it is shown in figure 20. It was a 40-percent spooldown airstart attempt at VC = 160 knots at 7600 m. Following the burner light at t = 35 sec, N2 continued to decrease, while FTIT increased rapidly, even with the fuel flow at the minimum value. When the FTIT reached the maximum allowable value of 800° C, the pilot shut down the engine.

Summary of Spooldown Airstart Success

Figure 21 summarizes the successful and unsuccessful spooldown airstarts. All airstarts at airspeeds of 200 knots and above were successful. At VC = 175 knots, all 25-percent spooldowns were unsuccessful, and 40-percent spooldowns above 8000 m were unsuccessful. All spooldown airstarts at VC = 150 knots were unsuccessful. The pilot's handbook airstart limit for the F100 engine with the standard control system is also shown in figure 21. The DEEC provides airstart capability at least 50 knots lower than the handbook limit.

Comparison of Flight to Altitude Facility Test Results

The DEEC airstart results from the flight tests are compared to the altitude facility test results of reference 3. The lowest airspeed at which spooldown airstarts were successful is shown in figure 22. For 40-percent spooldown airstarts (figure 22(a)) and 25-percent spooldowns (figure 22(b)) very good agreement is shown between the flight and altitude test results. This very good agreement is probably due to the closed-loop features in the DEEC which tend to compensate for any small differences between the flight and facility conditions.

CONCLUDING REMARKS

A series of airstarts were conducted with the DEEC-equipped F100 engine in an F-15 airplane. The airstart envelope and time required for airstarts were defined. The success of an airstart is most heavily dependent on airspeed. Spooldown airstarts at 200 knots and higher were all successful. Spooldown airstart times ranged from 45 sec at 250 knots to 135 sec at 200 knots. JFS-assisted airstarts were conducted over a wide range of airspeeds, and airstart times varied from 35 to 60 sec. The effect of altitude on airstarts was small. The airstart flight test results agreed closely with previous altitude facility data.

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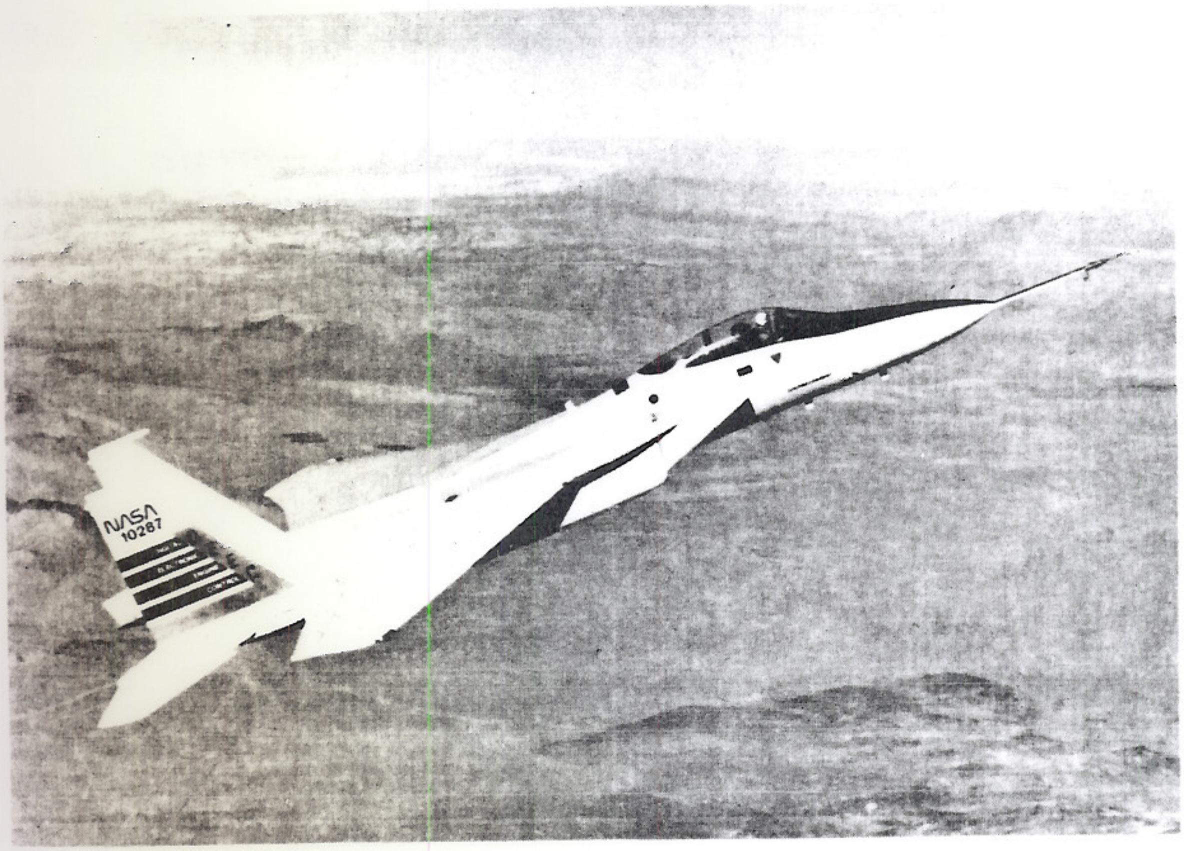

Figure 1. Photograph of the F-15 airplane

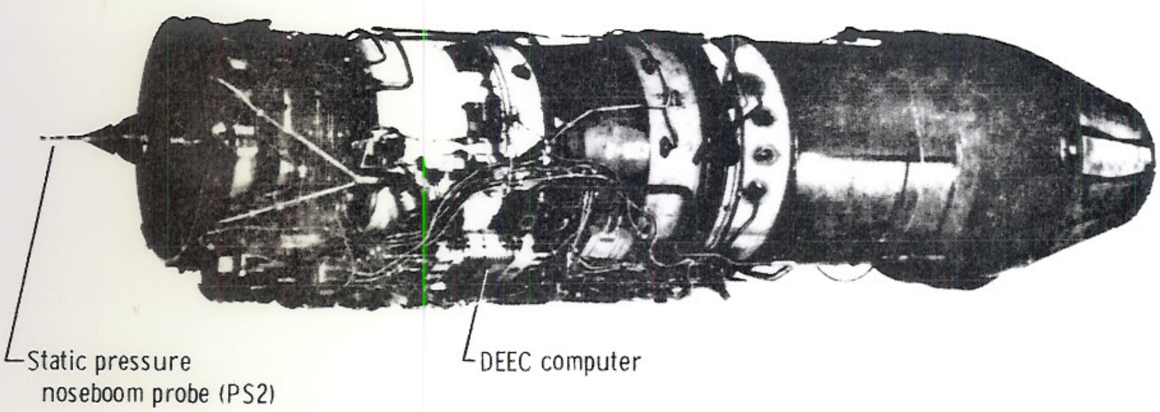

Figure 2. Photograph of the DEEC test engine

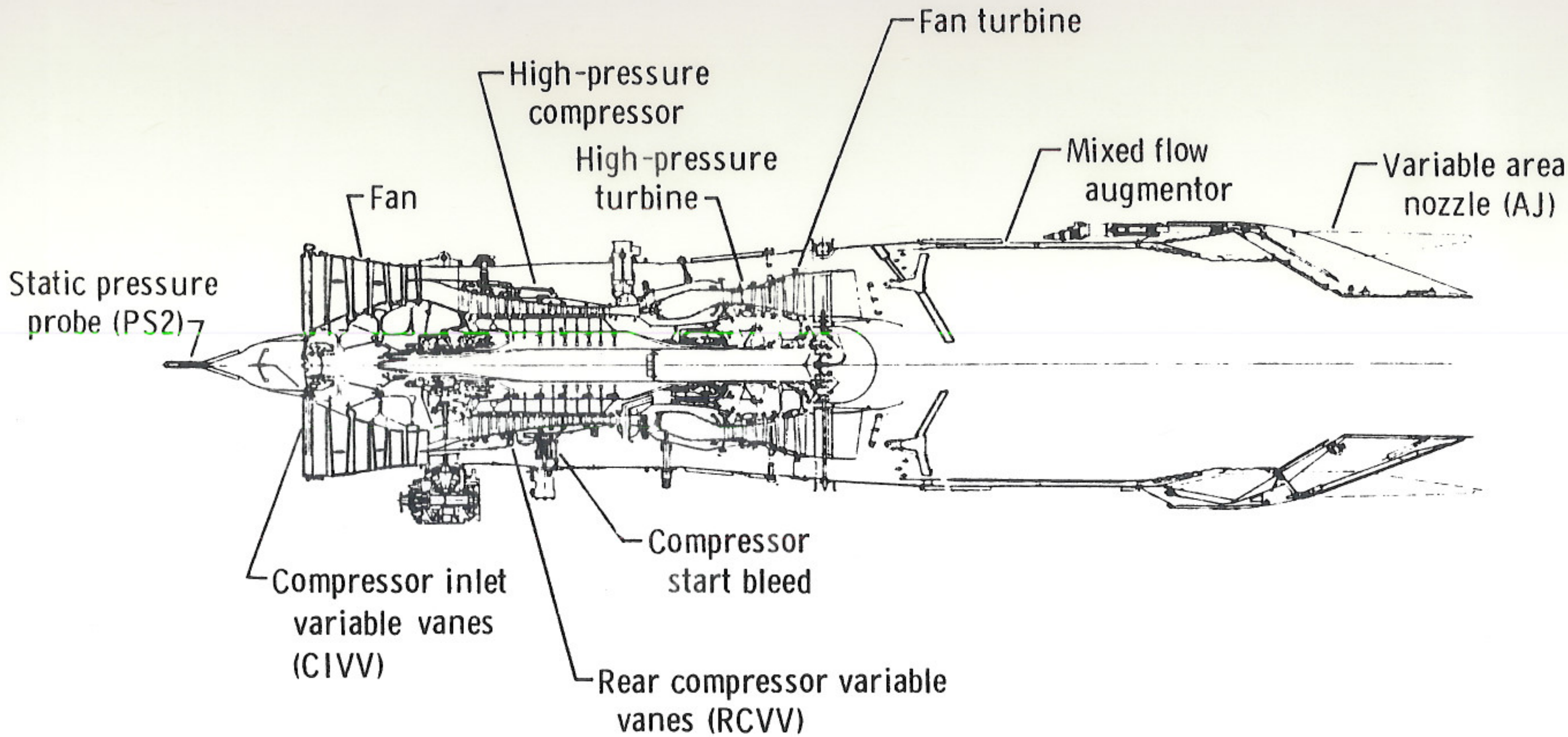

Figure 3. Cutaway view of the F100 DEEC engine

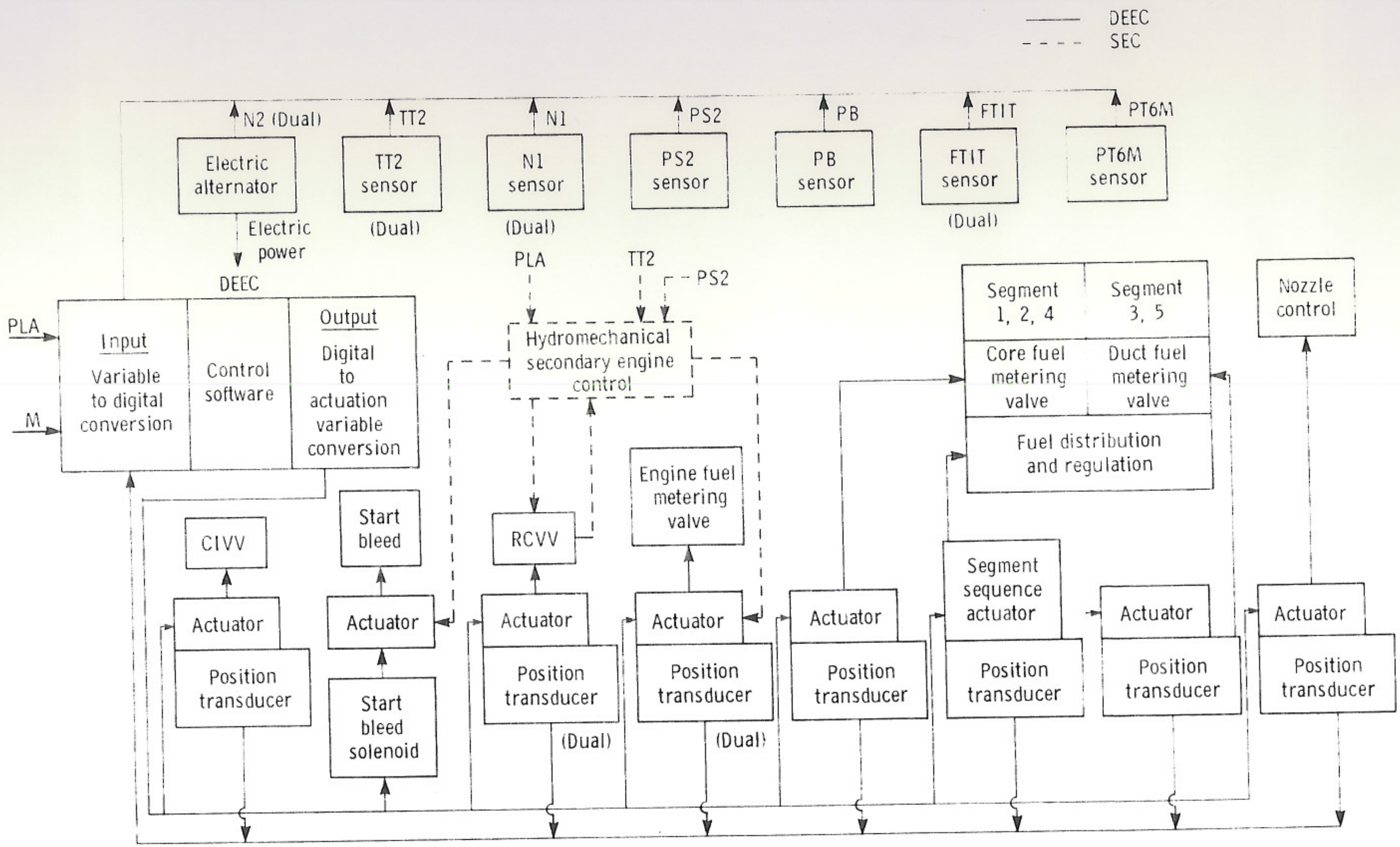

Figure 4. Block diagram of the DEEC control system

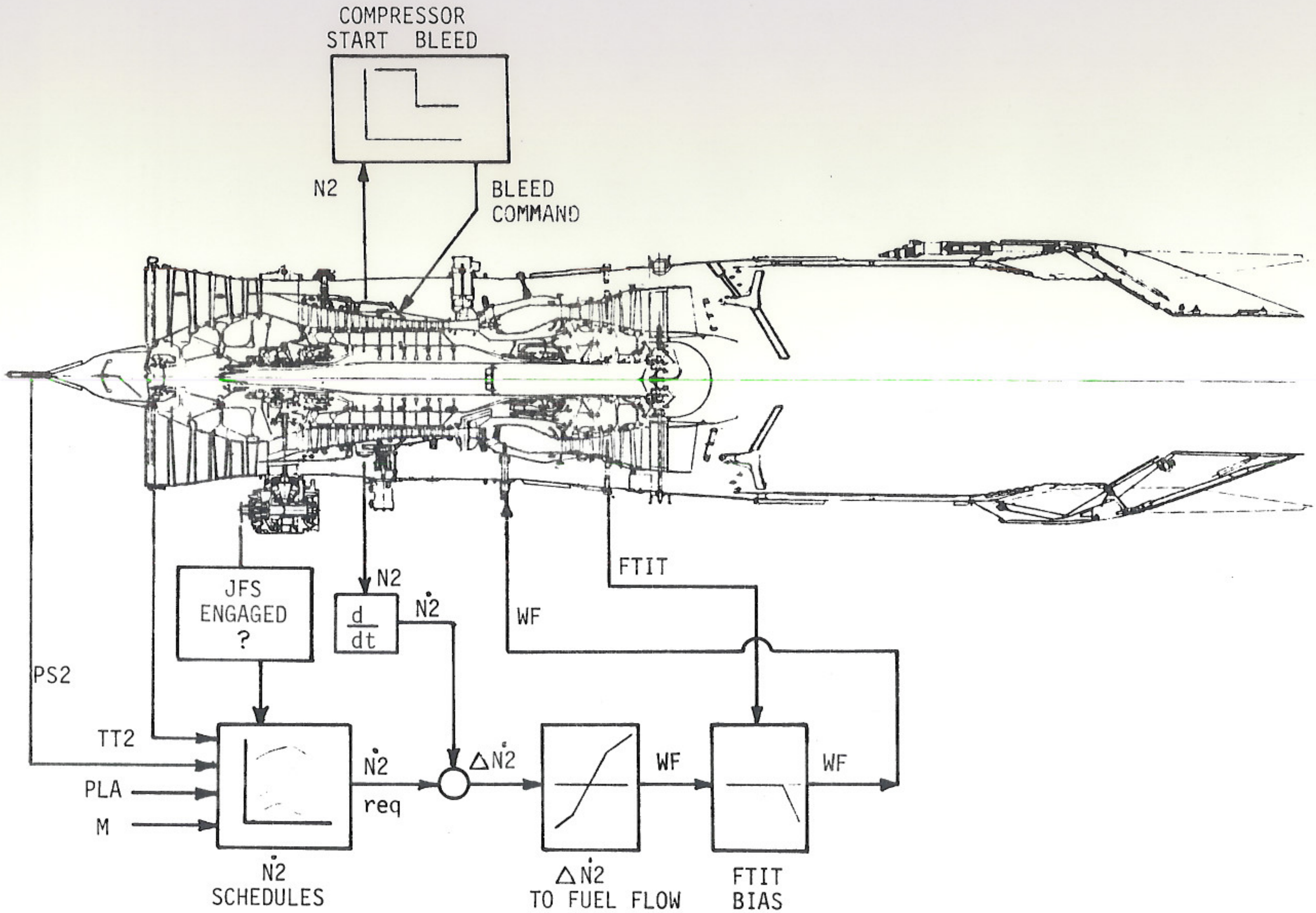

Figure 5. DEEC airstart logic

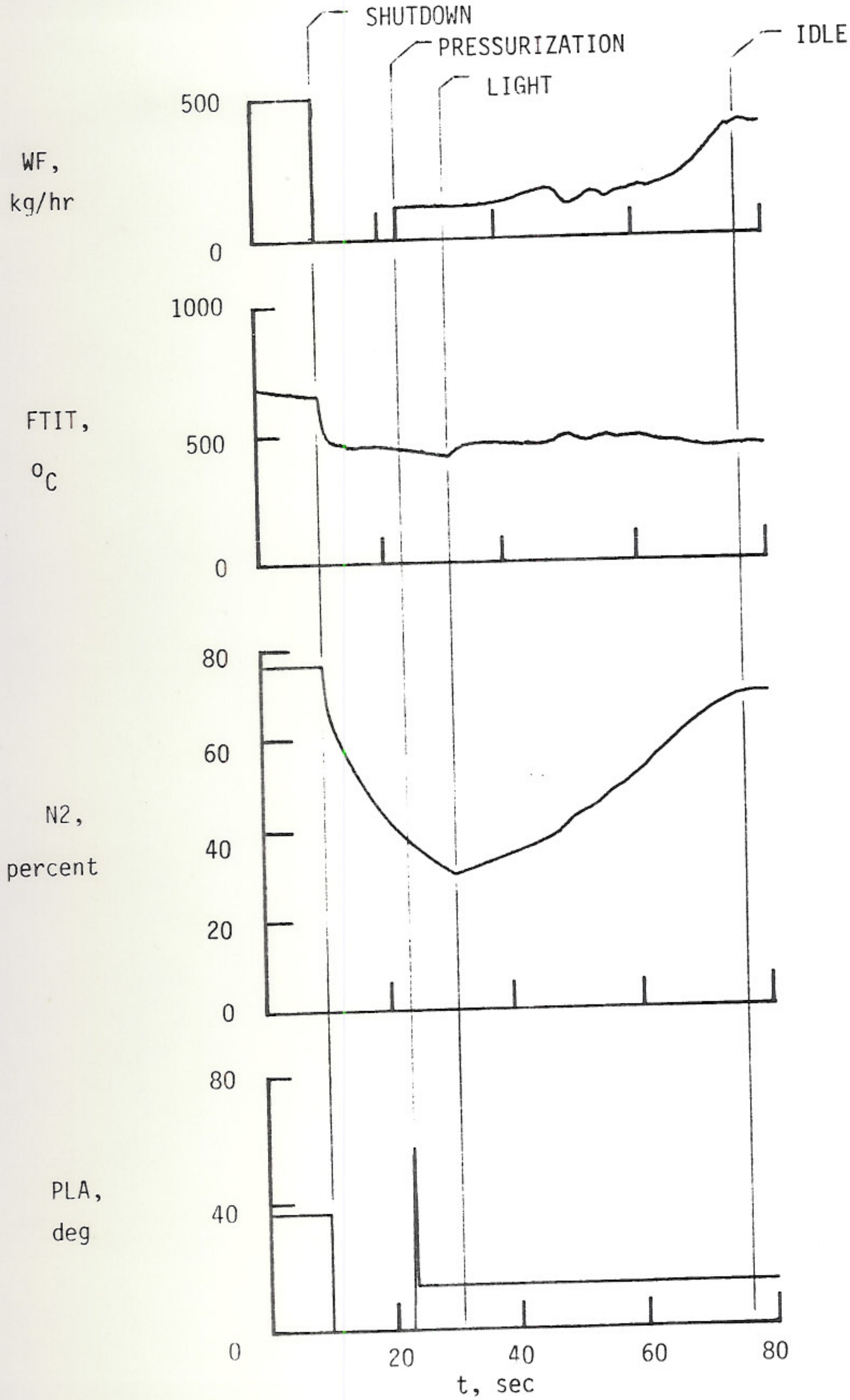

Figure 6. DEEC 40-percent spooldown airstart. VC=250 knots, HP = 9100 m

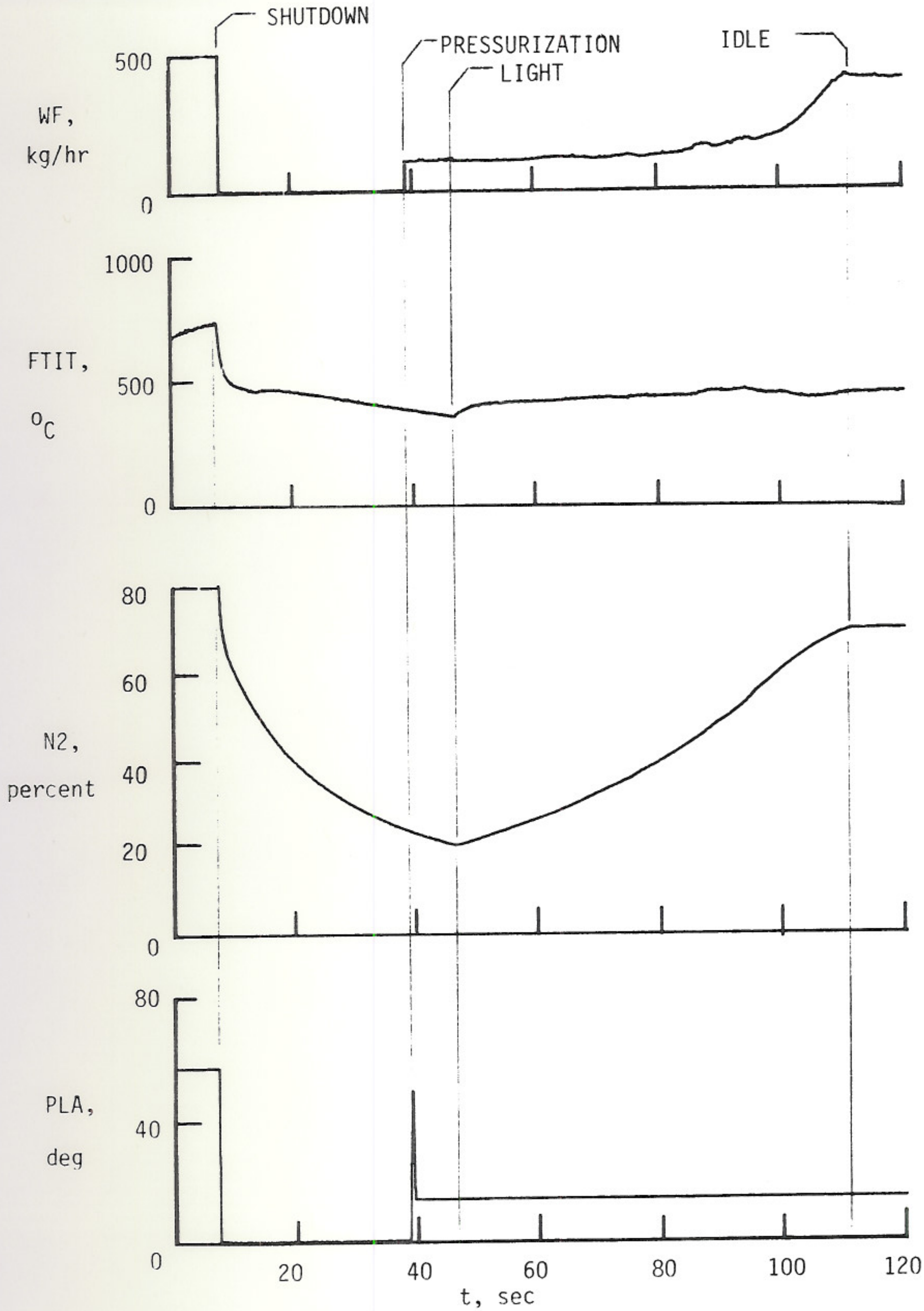

Figure 7. DEEC 25-percent spooldown airstart. VC = 250 knots, HP = 9100 m

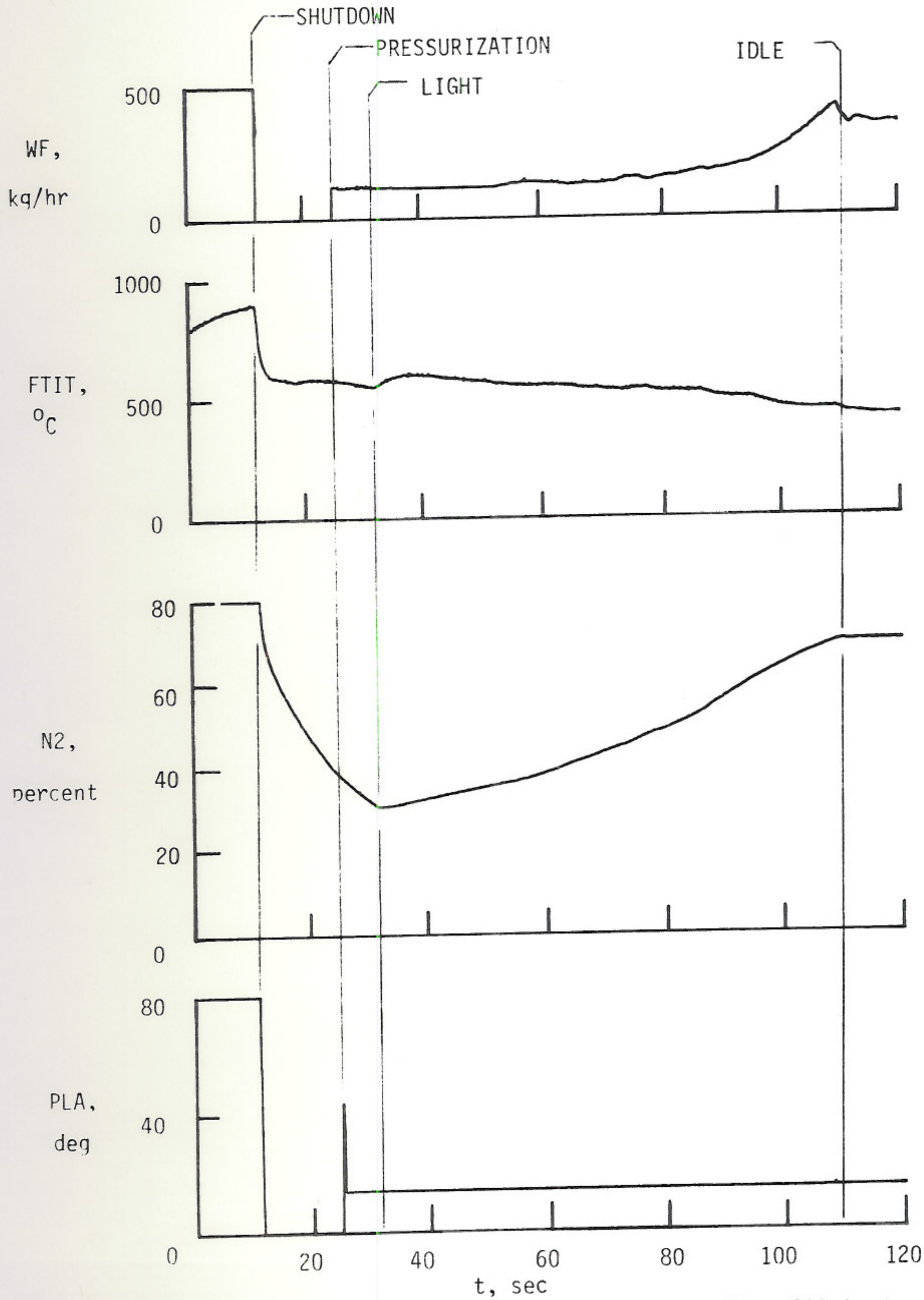

Figure 8. - DEEC 40-percent spooldown airstart. VC = 200 knots, HP = 9250 m.

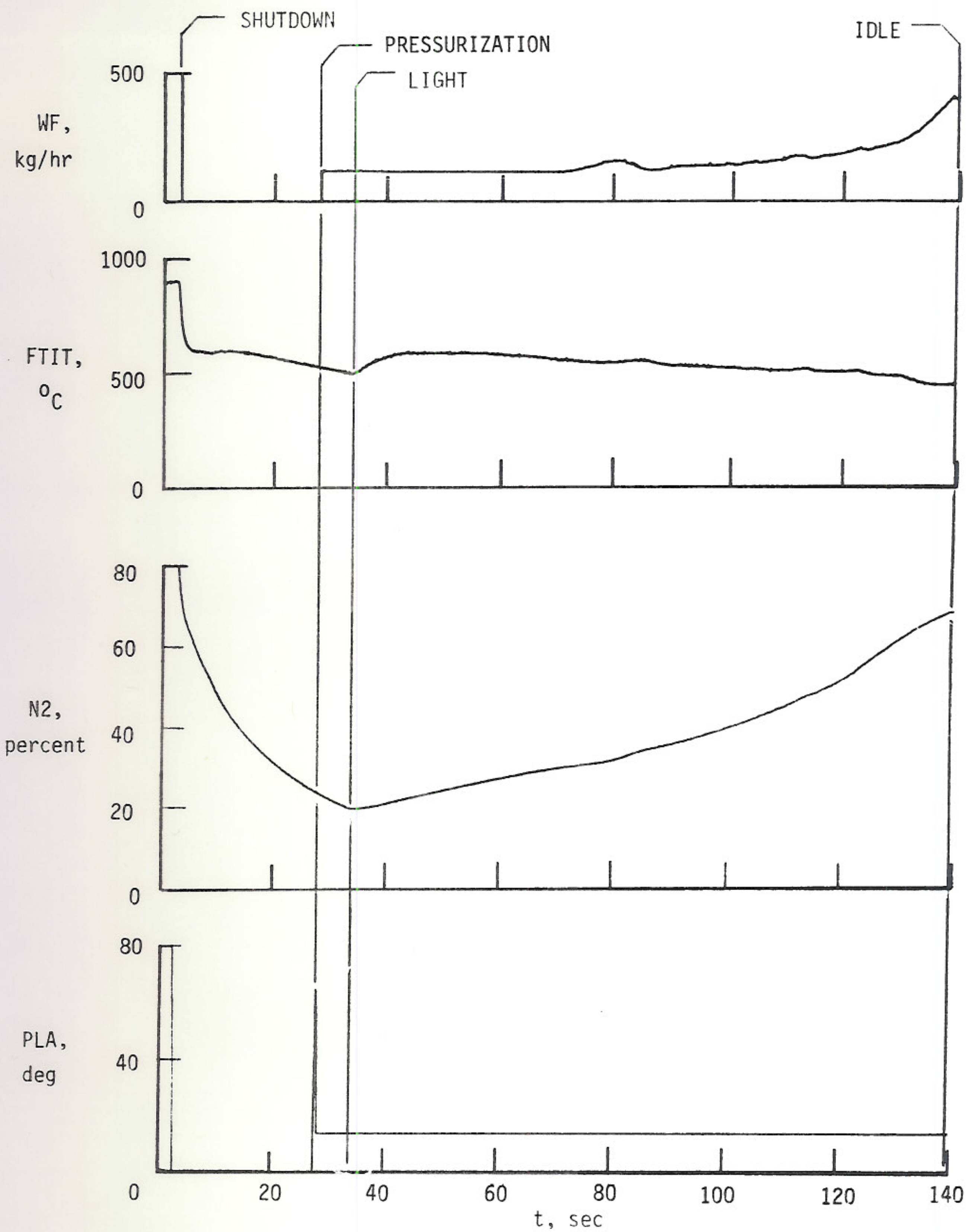

Figure 9. DEEC 25-percent spooldown airstart. VC = 200 knots, HP = 7600 m

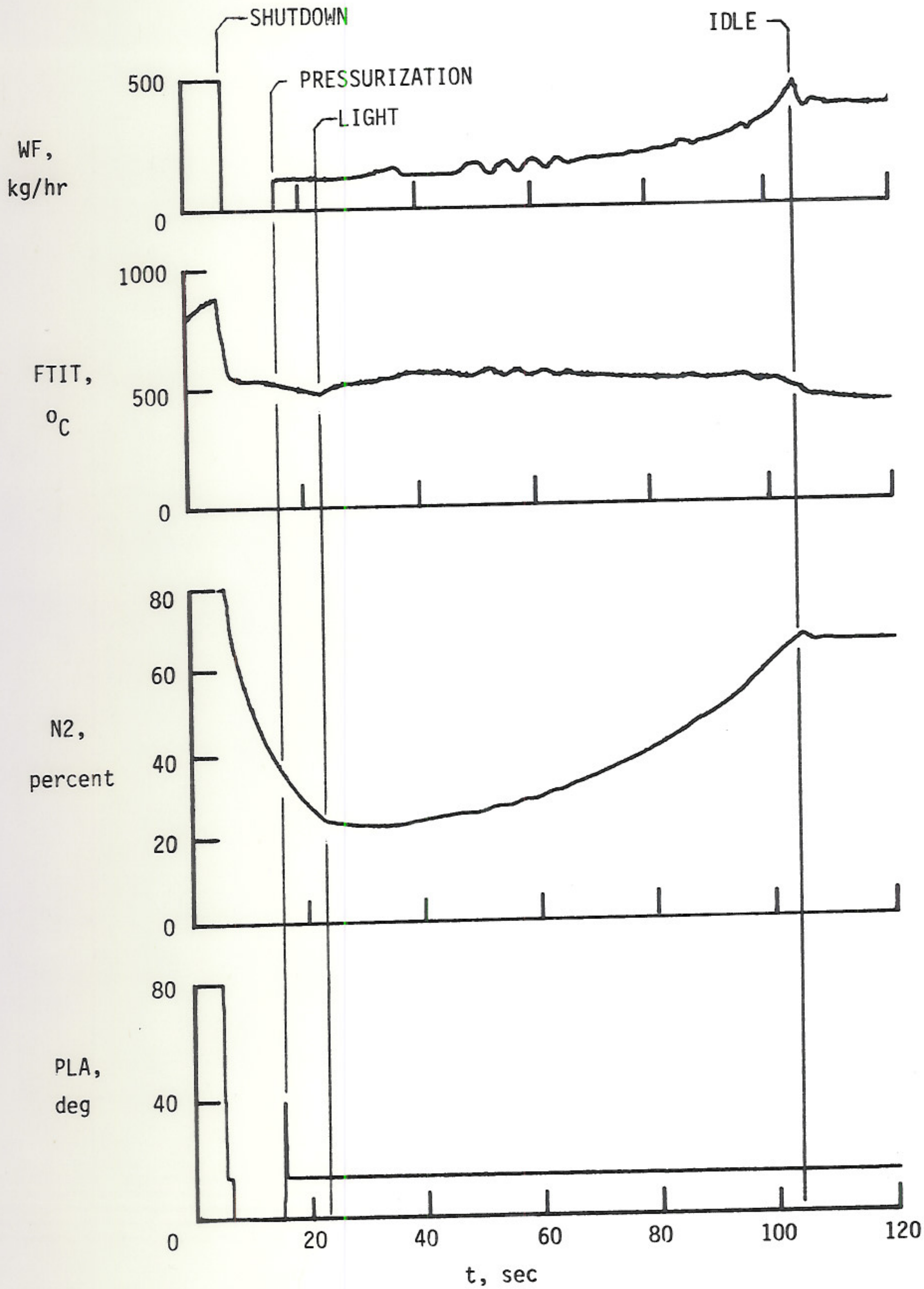

Figure 10. DEEC 40-percent spooldown airstart. VC = 200 knots, HP = 4600 m

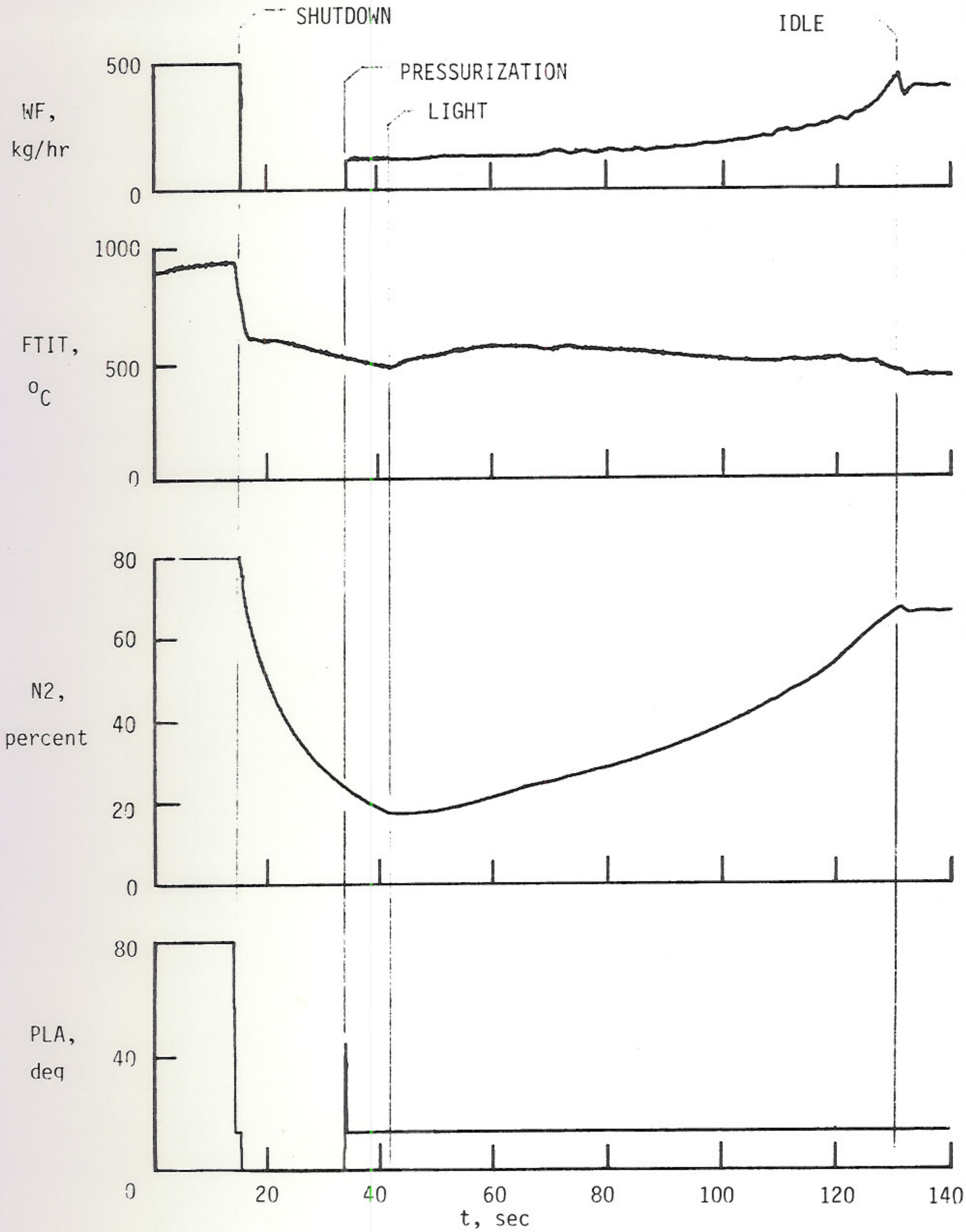

Figure 11. DEEC 25-percent spooldown airstart. VC = 200 knots, HP = 4600 m

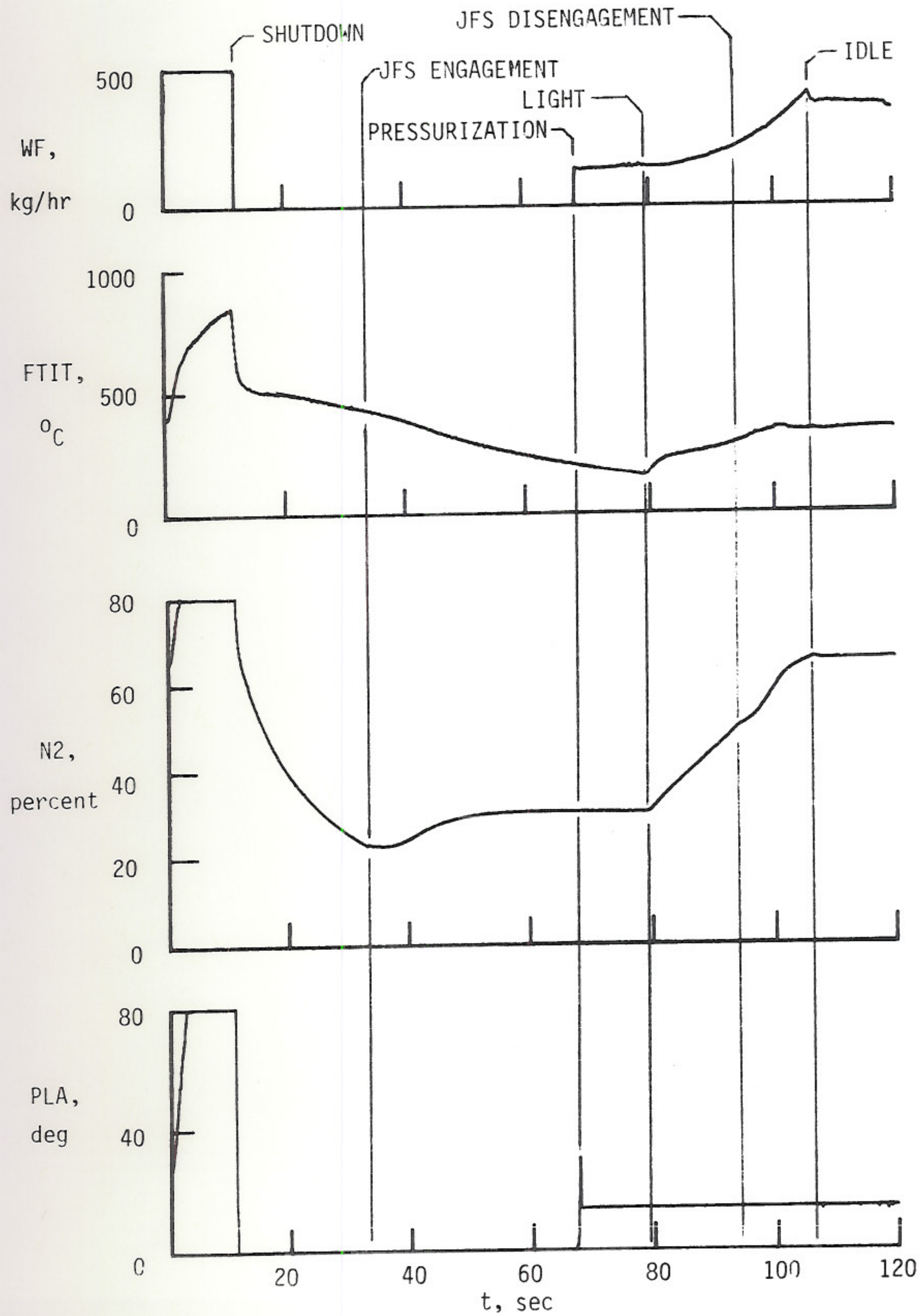

Figure 12. DEEC JFS-assisted airstart. VC = 255 knots, HP = 6100 m

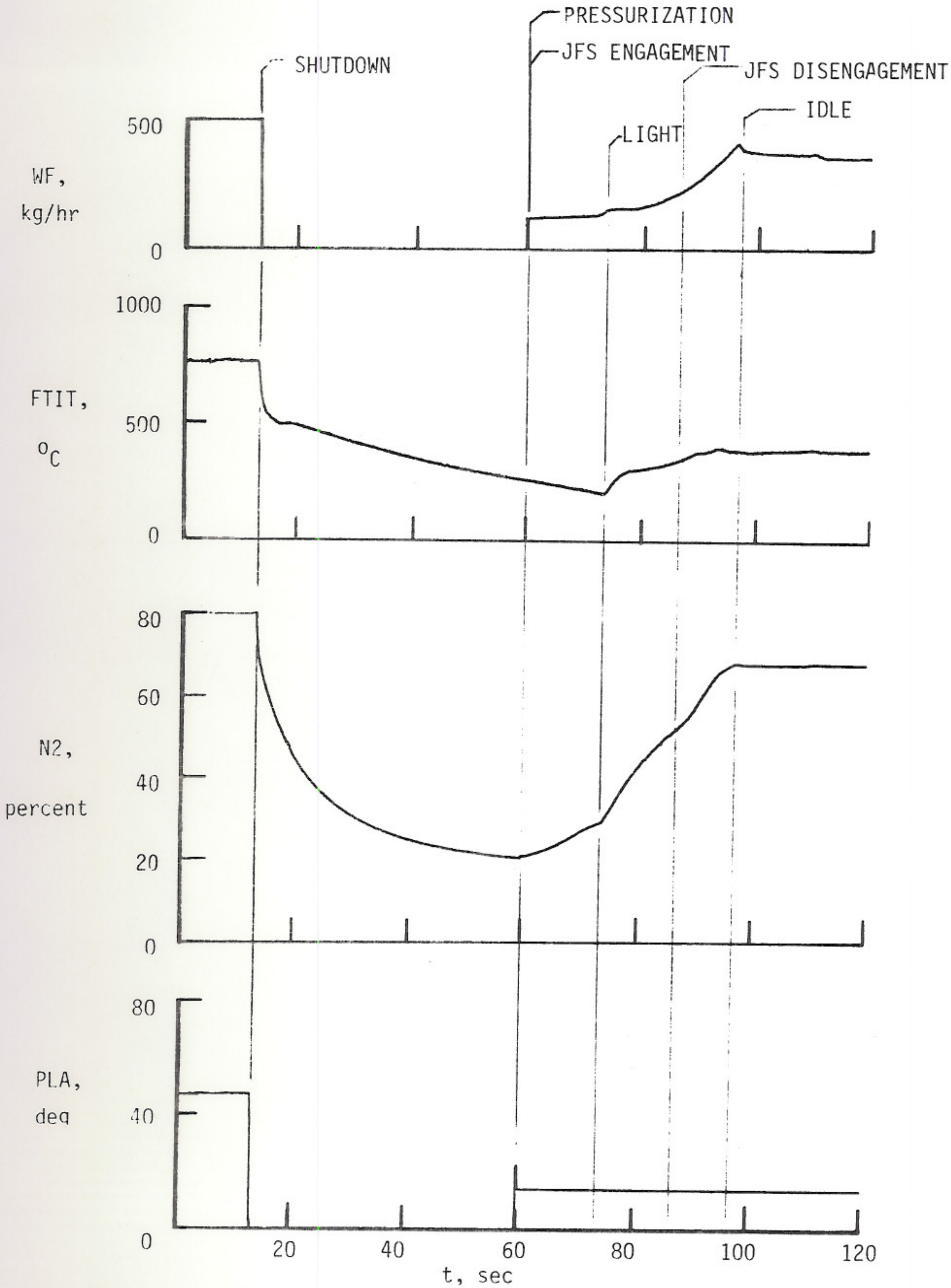

Figure 13. DEEC JFS-assisted airstart. VC = 345 knots, HP = 5200 m

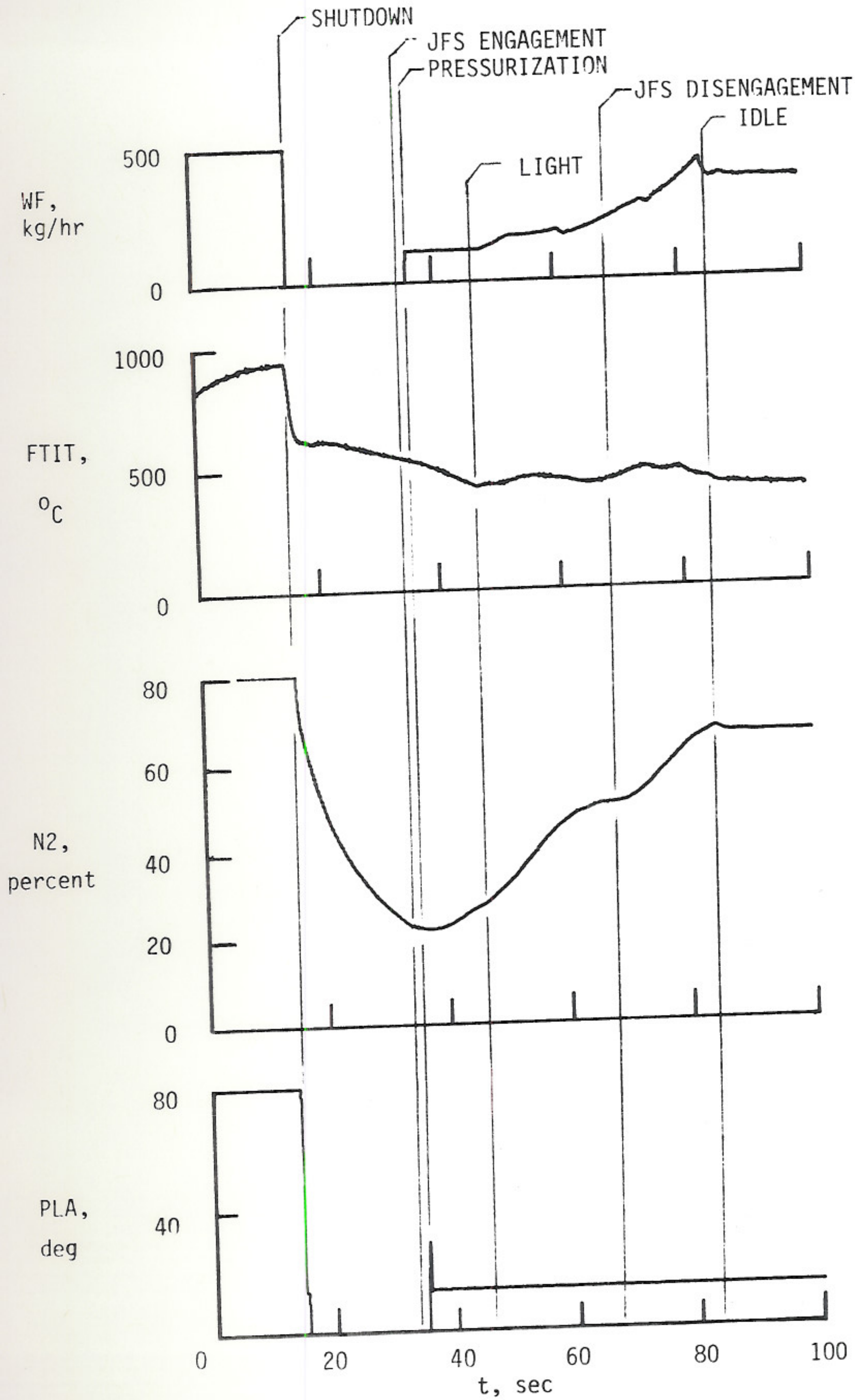

Figure 14. DEEC JFS-assisted airstart, VC = 210 knots, HP = 6100 m

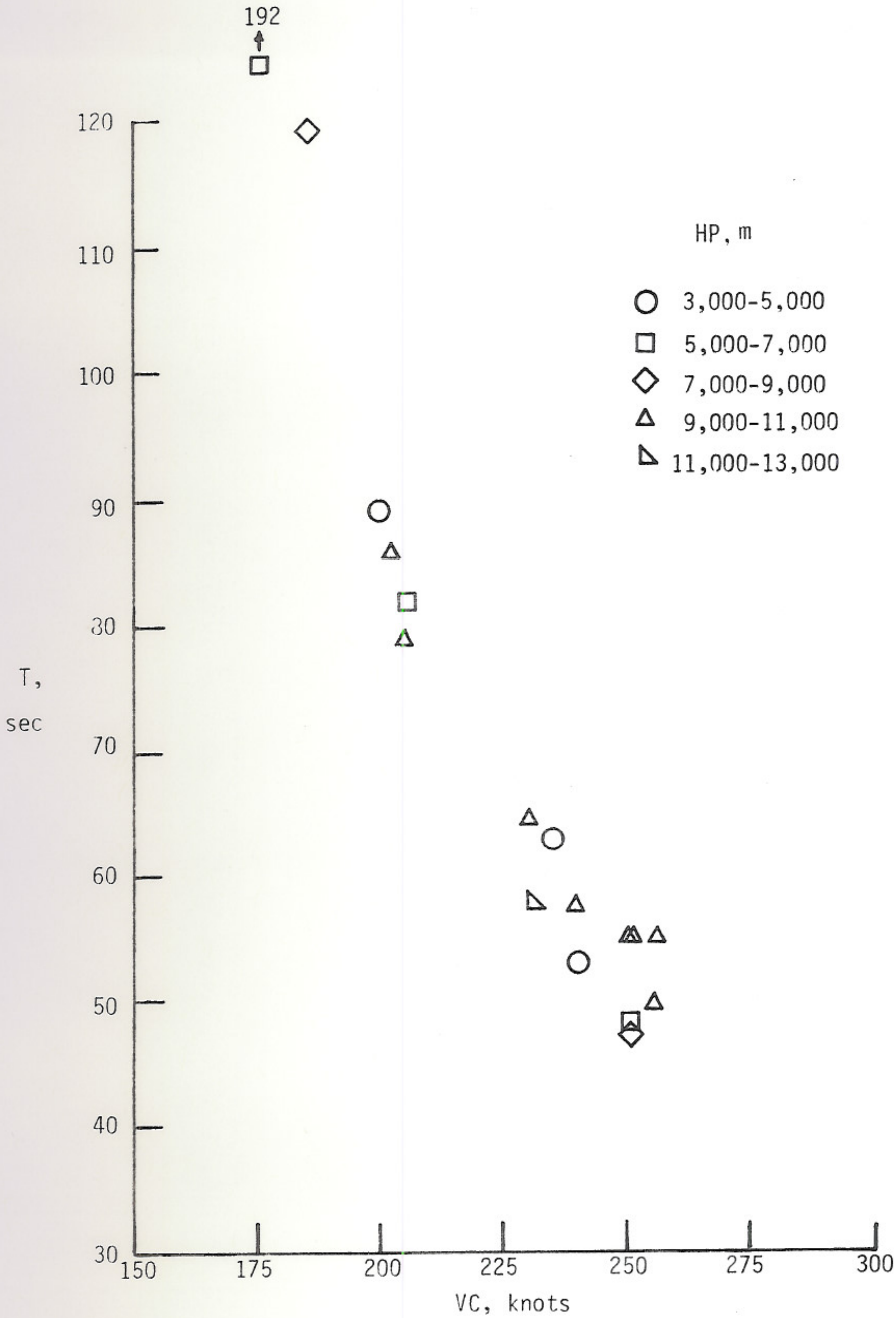

Figure 15. Effect of airspeed on airstart time for 40-percent spooldown airstart

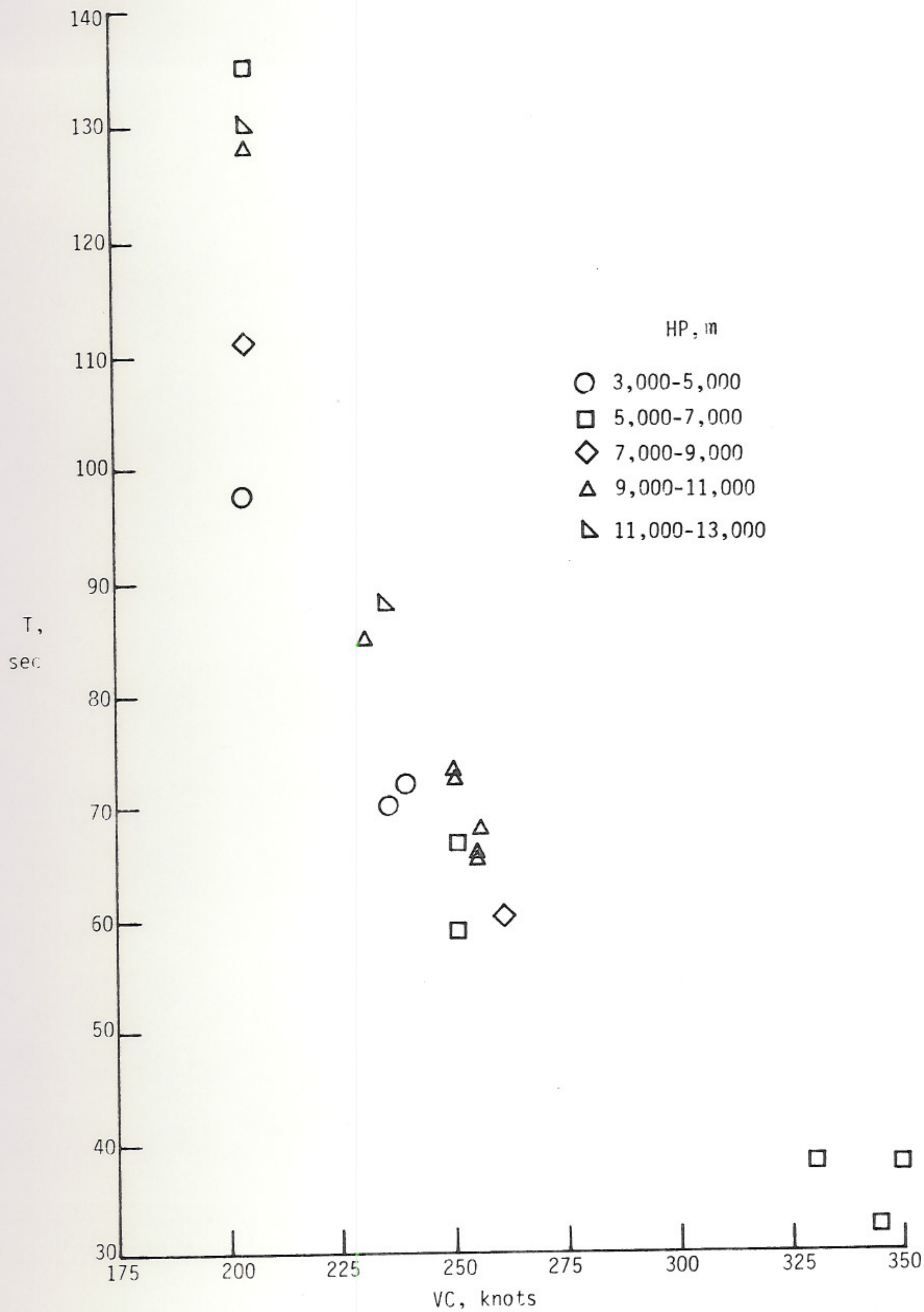

Figure 16. Effect of airspeed on airstart time for 25-percent spooldown

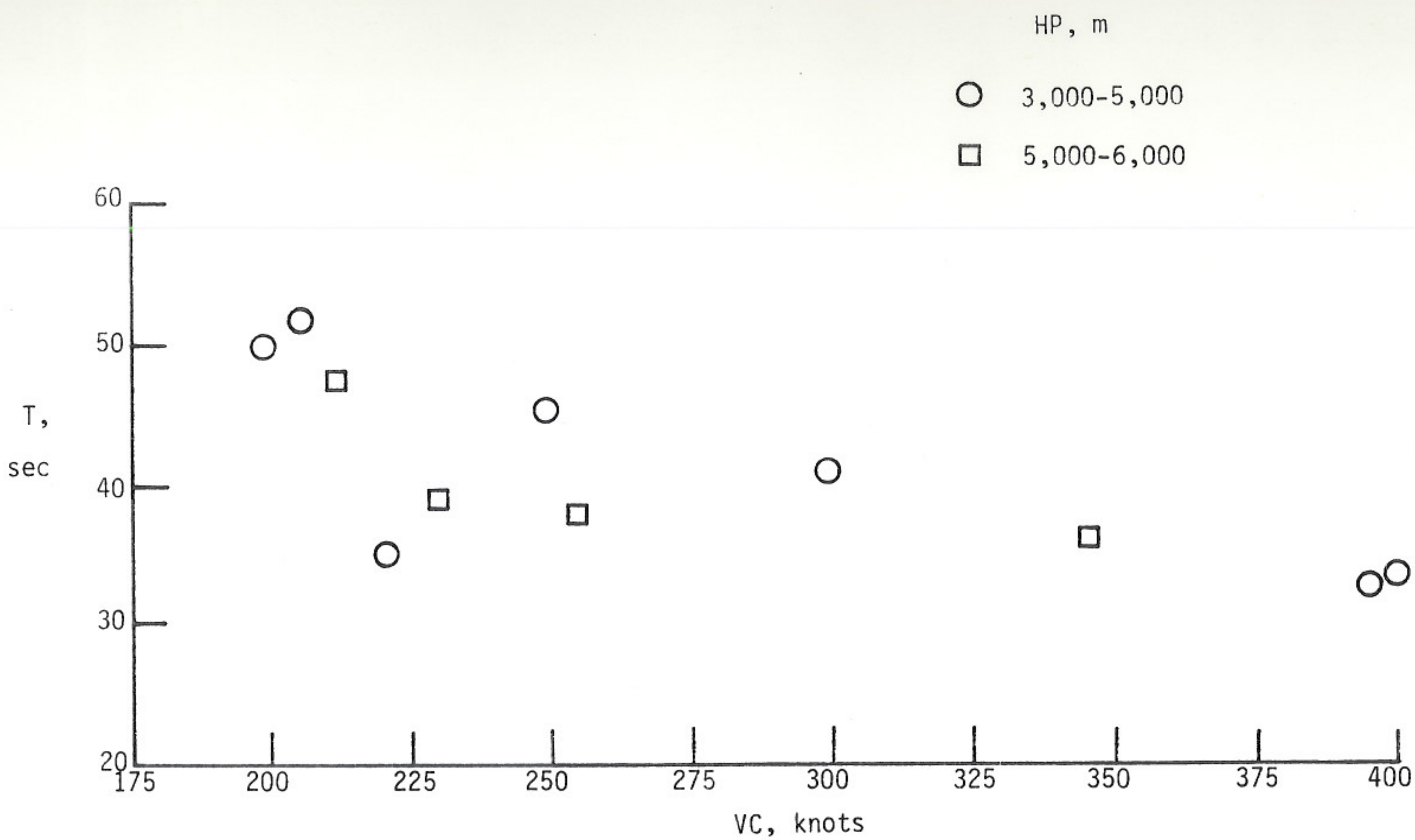

Figure 17. Effect of airspeed on airstart time for JFS-assisted airstarts

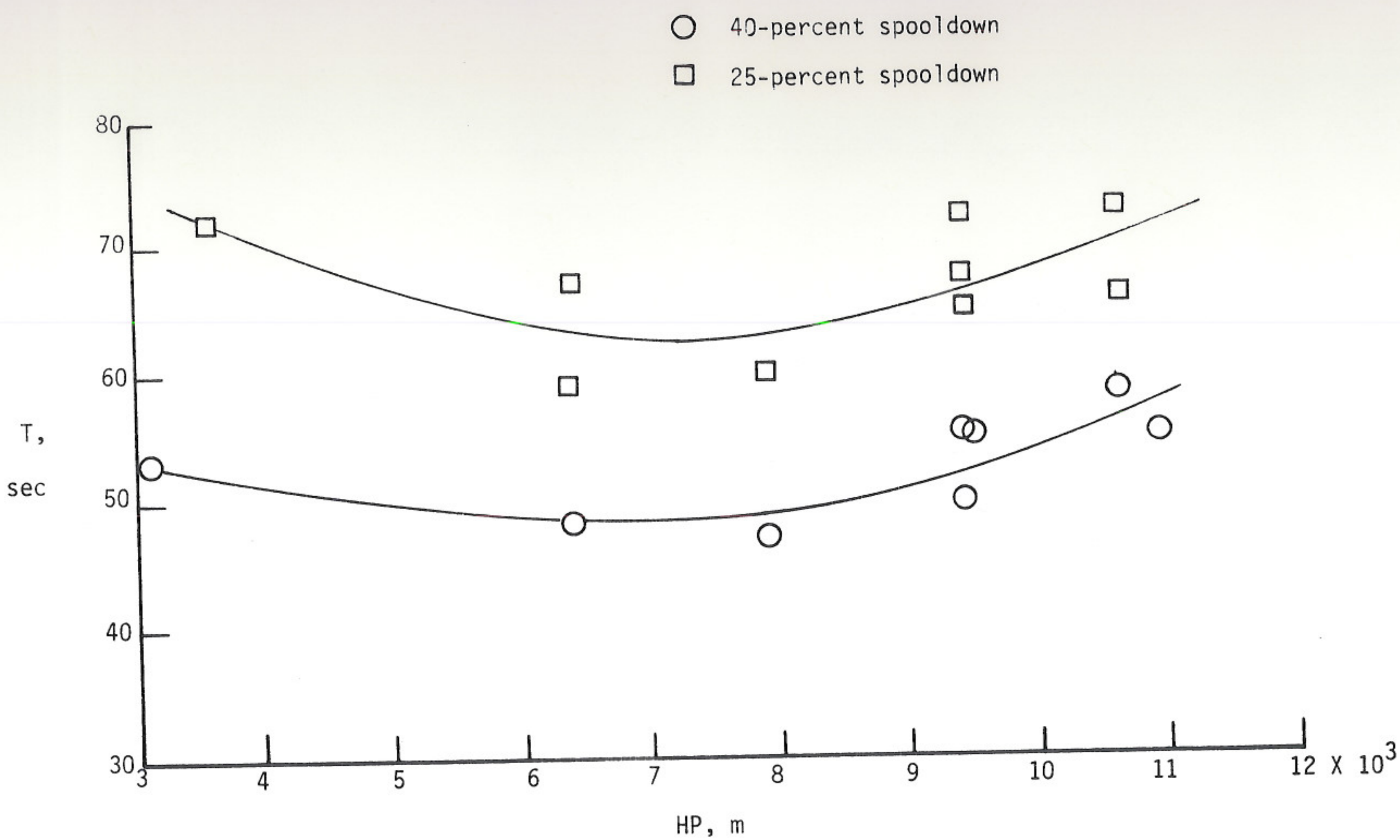

Figure 18. Effect of altitude on airstart time for spooldown airstarts. VC ≃ 250 knots

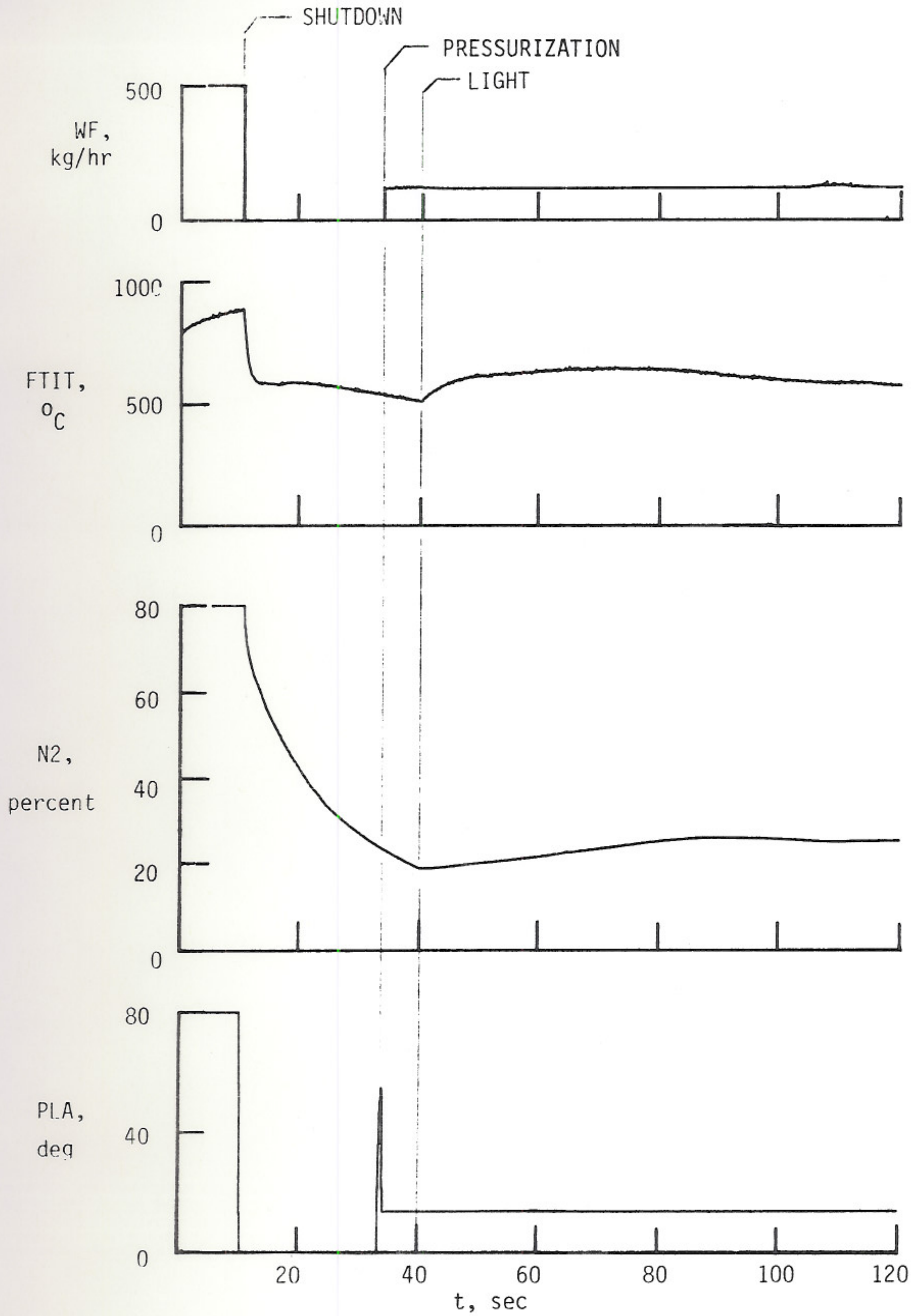

Figure 19. Unsuccessful DEEC 25-percent spooldown airstart. VC = 180 knots, HP = 7600 m

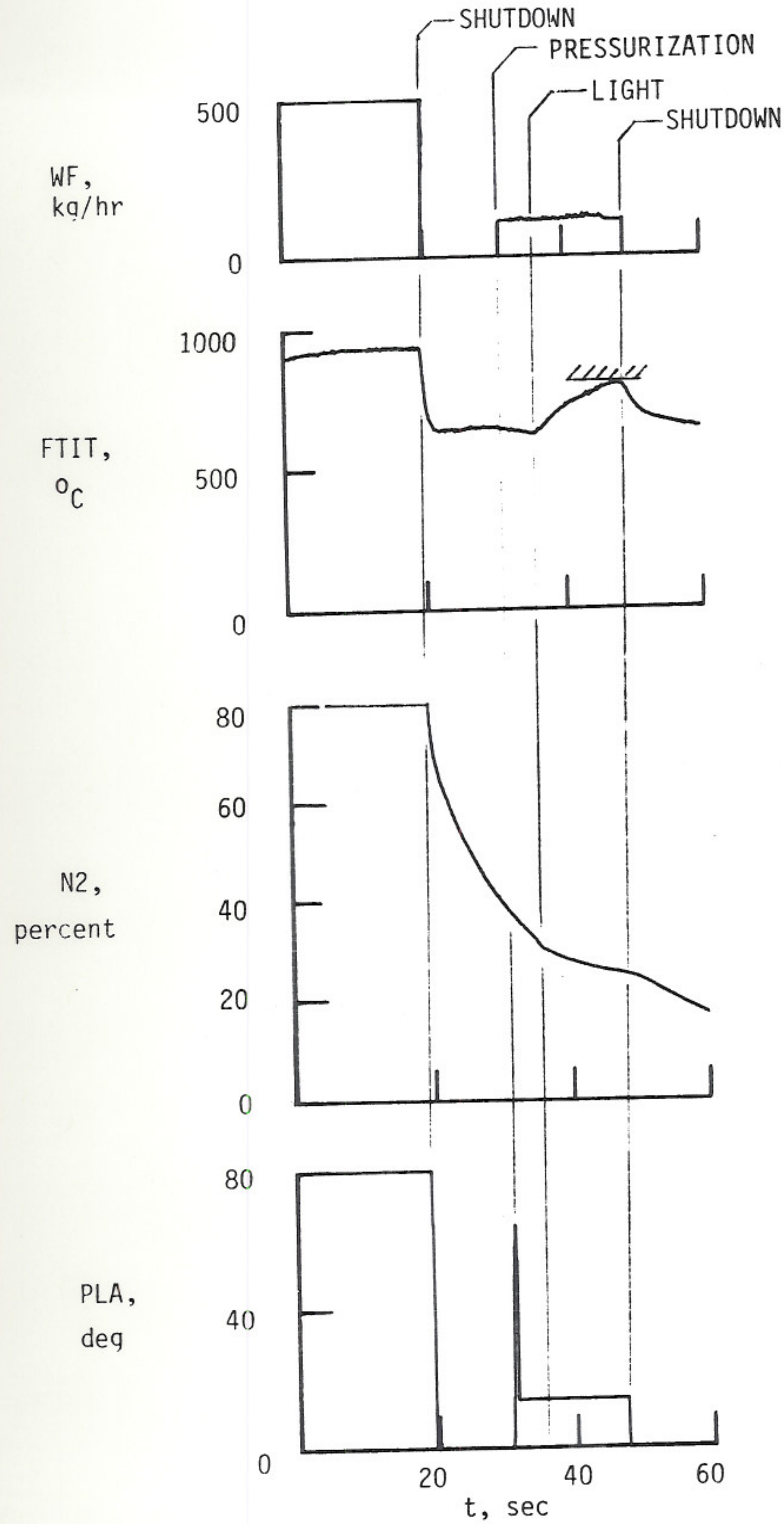

Figure 20. Unsuccessful DEEC 40-percent spooldown airstart. VC = 160 knots, HP = 7600 m

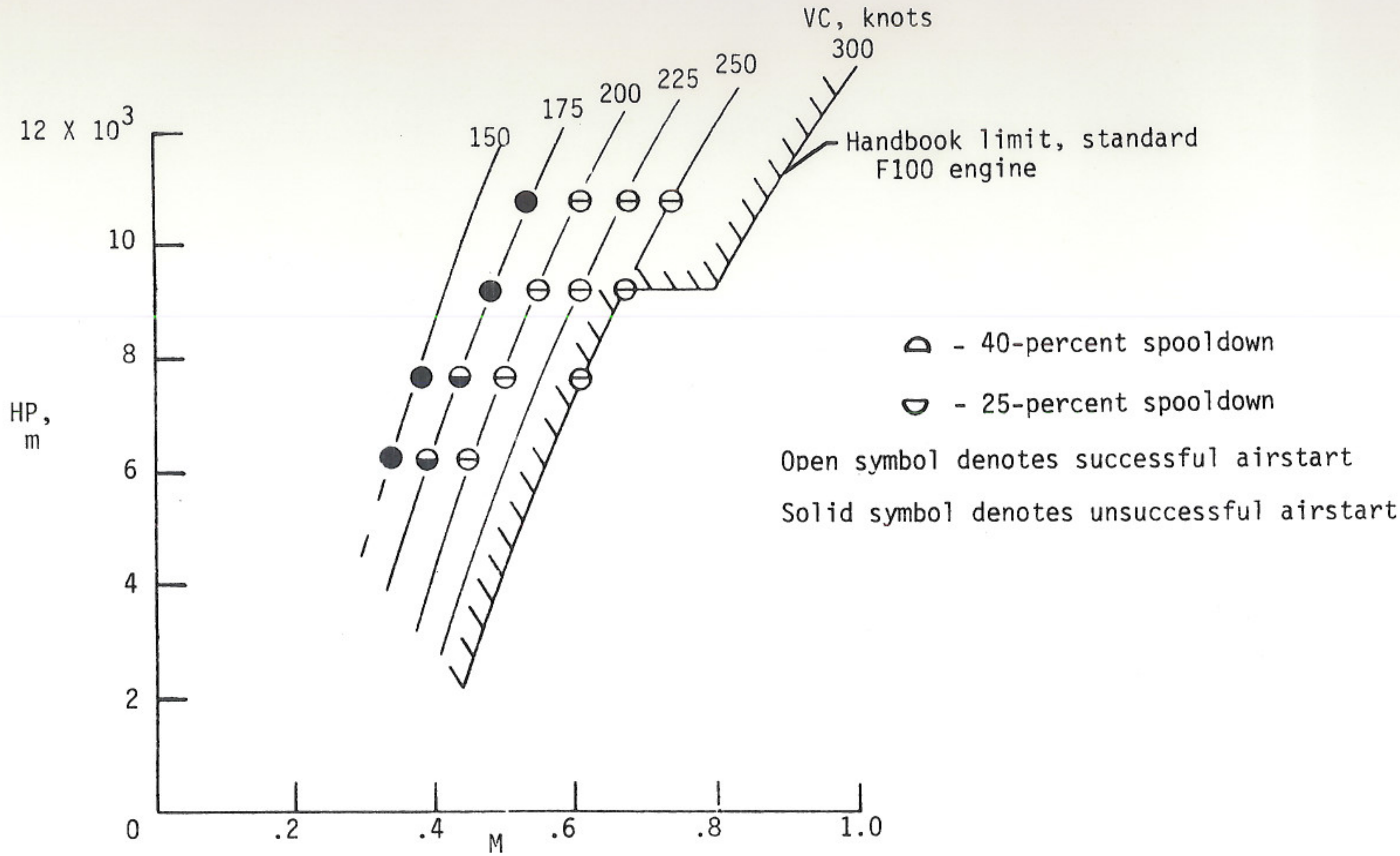

Figure 21. Summary of DEEC spooldown airstart test success

Open symbols denote data from altitude facility (ref. 3)
Solid symbols denote flight data

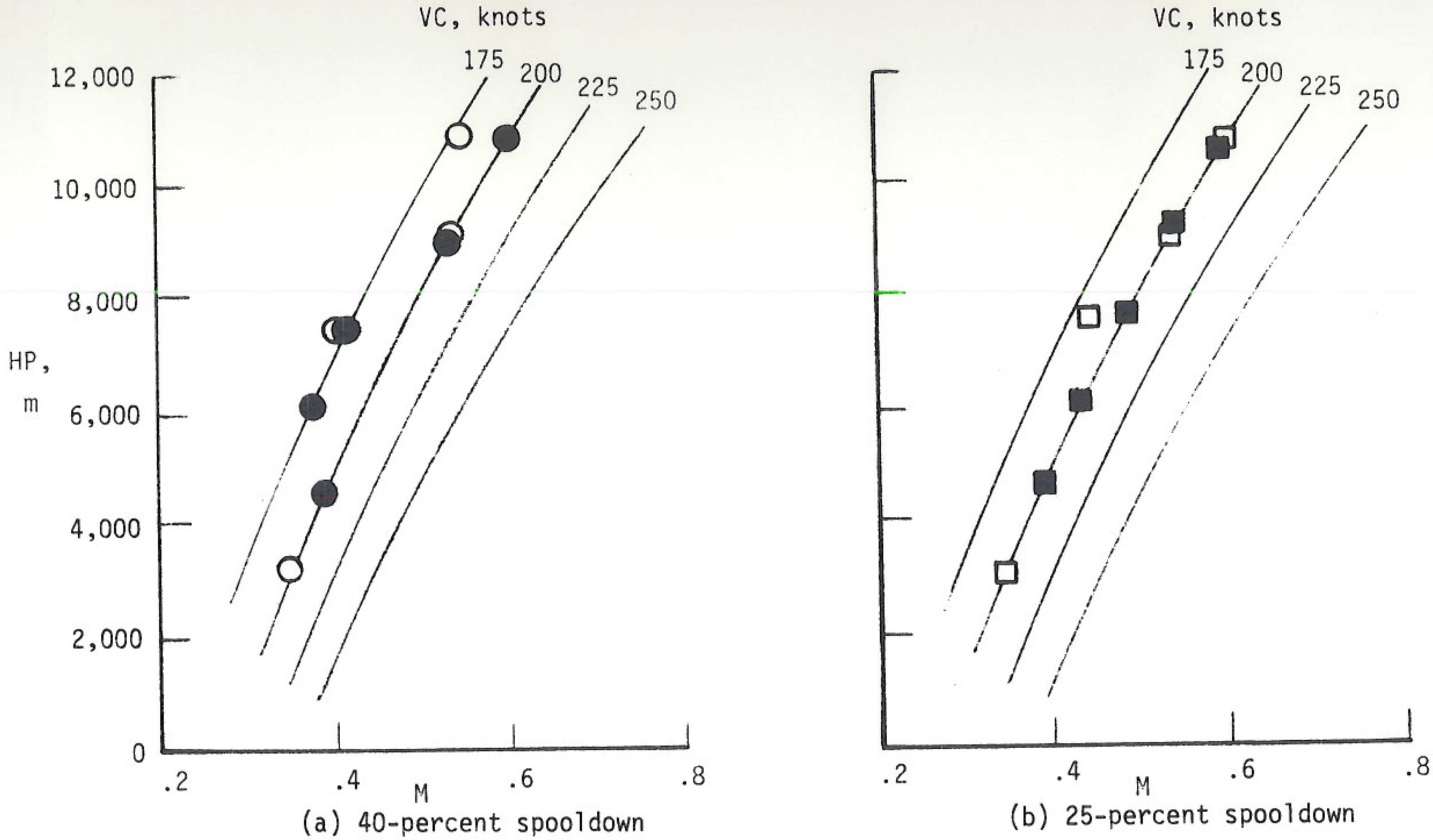

Figure 22. Comparison of lowest airspeed for successful DEEC airstarts between flight tests and altitude facility tests

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16. Abstract

The airstart performance of the F100 engine equipped with a digital electronic engine control (DEEC) system was evaluated in an F-15 airplane. The DEEC system incorporates closed-loop airstart logic for improved capability. Spooldown and jet fuel starter-assisted airstarts were made over a range of airspeeds and altitudes. All jet fuel starter-assisted airstarts were successful, with airstart times varying from 35 to 60 sec. All spooldown airstarts at airspeeds of 200 knots and higher were successful; airstart times ranged from 45 sec at 250 knots to 135 sec at 200 knots. The effects of altitude on airstart success and time were small. The flight results agreed closely with previous altitude facility test results. The DEEC system provided successful airstarts at airspeeds at least 50 knots lower than the standard F100 engine control system.

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